5. ANALYSIS

5.1 Analysis Requirements

5.1.1 Analysis Objective

The objective of seismic analysis is to assess the force and deformation demands and capacities on the structural system and its individual components. Equivalent static analysis and linear elastic dynamic analysis are the appropriate analytical tools for estimating the displacement demands for Ordinary Standard bridges. Inelastic static analysis is the appropriate analytical tool to establishing the displacement capacities for Ordinary Standard bridges.

5.2 Analytical Methods

5.2.1 Equivalent Static Analysis (ESA)

ESA can be used to estimate displacement demands for structures where a more sophisticated dynamic analysis will not provide additional insight into behavior. ESA is best suited for structures or individual frames with well balanced spans and uniformly distributed stiffness where the response can be captured by a predominant translational mode of vibration.

The seismic load shall be assumed as an equivalent static horizontal force applied to individual frames. The total applied force shall be equal to the product of the ARS and the tributary weight. The horizontal force shall be applied at the vertical center of mass of the superstructure and distributed horizontally in proportion to the mass distribution.

5.2.2 Elastic Dynamic Analysis (EDA)

EDA shall be used to estimate the displacement demands for structures where ESA does not provide an adequate level of sophistication to estimate the dynamic behavior. A linear elastic multi-modal spectral analysis utilizing the appropriate response spectrum shall be performed. The number of degrees of freedom and the number of modes considered in the analysis shall be sufficient to capture at least 90% mass participation in the longitudinal and transverse directions. A minimum of three elements per column and four elements per span shall be used in the linear elastic model.

EDA based on design spectral accelerations will likely produce stresses in some elements that exceed their elastic limit. The presence of such stresses indicates nonlinear behavior. The engineer should recognize that forces generated by linear elastic analysis could vary considerable from the actual force demands on the structure.
Sources of nonlinear response that are not captured by EDA include the effects of the surrounding soil, yielding of structural components, opening and closing of expansion joints, and nonlinear restrainer and abutment behavior. EDA modal results shall be combined using the complete quadratic combination (CQC) method.

Multi-frame analysis shall include a minimum of two boundary frames or one frame and an abutment beyond the frame under consideration. See Figure 5.1.

5.2.3 Inelastic Static Analysis (ISA)

ISA, commonly referred to as "push over" analysis, shall be used to determine the reliable displacement capacities of a structure or frame as it reaches its limit of structural stability. ISA shall be performed using expected material properties of modeled members. ISA is an incremental linear analysis, which captures the overall nonlinear behavior of the elements, including soil effects, by pushing them laterally to initiate plastic action. Each increment pushes the frame laterally, through all possible stages, until the potential collapse mechanism is achieved. Because the analytical model accounts for the redistribution of internal actions as components respond inelastically, ISA is expected to provide a more realistic measure of behavior than can be obtained from elastic analysis procedures.

5.3 Structural System "Global" Analysis

Structural system or global analysis is required when it is necessary to capture the response of the entire bridge system. Bridge systems with irregular geometry, in particular curved bridges and skew bridges, multiple transverse expansion joints, massive substructures components, and foundations supported by soft soil can exhibit dynamic response characteristics that are not necessarily obvious and may not be captured in a separate subsystem analysis [7].

Two global dynamic analyses are normally required to capture the assumed nonlinear response of a bridge because it possesses different characteristics in tension versus compression [3].

In the tension model, the superstructure joints including the abutments are released longitudinally with truss elements connecting the joints to capture the effects of the restrainers. In the compression model, all of the truss (restrainer) elements are inactivated and the superstructure elements are locked longitudinally to capture structural response modes where the joints close up, mobilizing the abutments when applicable.

The structure's geometry will dictate if both a tension model and a compression model are required. Structures with appreciable superstructure curvature may require additional models, which combine the characteristics identified for the tension and compression models.

Long multi-frame bridges shall be analyzed with multiple elastic models. A single multi-frame model may not be realistic since it cannot account for out-of-phase movement among the frames and may not have enough nodes to capture all of the significant dynamic modes.

Each multi-frame model should be limited to five frames plus a boundary frame or abutment on each end of the model. Adjacent models shall overlap each other by at least one useable frame, see Figure 5.1.

The boundary frames provide some continuity between adjacent models but are considered redundant and their analytical results are ignored. A massless spring should be attached to the dead end of the boundary frames to represent the stiffness of the remaining structure. Engineering judgement should be exercised when interpreting the deformation results among various sets of frames since the boundary frame method does not fully account for the continuity of the structure [3].

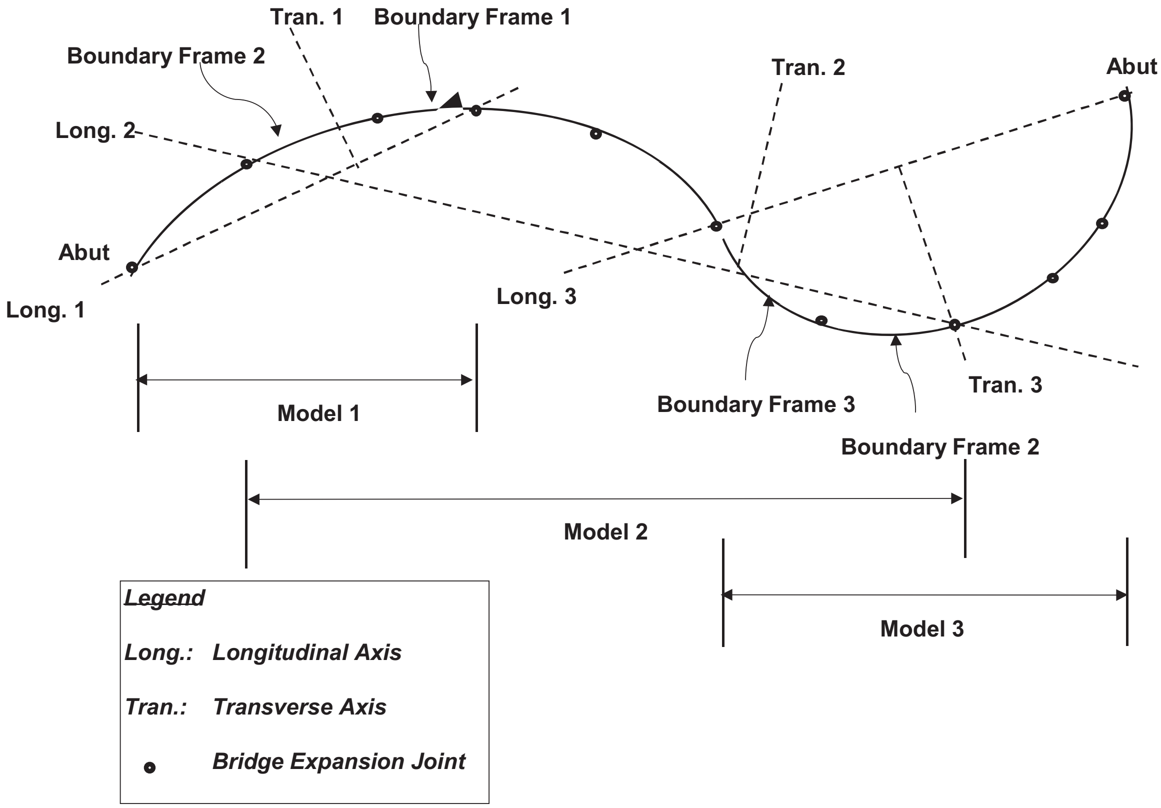

Figure 5.1 EDA Modeling Techniques

5.4 Stand-Alone "Local" Analysis

Stand-alone analysis quantifies the strength and ductility capacity of an individual frame, bent, or column. Stand-alone analysis shall be performed in both the transverse and longitudinal directions. Each frame shall meet all SDC requirements in the stand-alone condition.

5.4.1 Transverse Stand-Alone Analysis

Transverse stand-alone frame models shall assume lumped mass at the columns. Hinge spans shall be modeled as rigid elements with half of their mass lumped at the adjacent column, see Figure 5.2. The transverse analysis of end frames shall include a realistic estimate of the abutment stiffness consistent with the abutment's expected performance. The transverse displacement demand at each bent in a frame shall include the effects of rigid body rotation around the frame's center of rigidity.

5.4.2 Longitudinal Stand-Alone Analysis

Longitudinal stand-alone frame models shall include the short side of hinges with a concentrated dead load, and the entire long side of hinges supported by rollers at their ends, see Figure 5.2. Typically the abutment stiffness is ignored in the stand-alone longitudinal model for structures with more than two frames, an overall length greater than 300 feet (90 m) or significant in plane curvature since the controlling displacement occurs when the frame is moving away from the abutment. A realistic estimate of the abutment stiffness may be incorporated into the stand-alone analysis for single frame tangent bridges and two frame tangent bridges less than 300 feet (90 m) in length.

5.5 Simplified Analysis

The two-dimensional plane frame "push over" analysis of a bent or frame can be simplified to a column model (fixed-fixed or fixed-pinned) if it does not cause a significant loss in accuracy in estimating the displacement demands or the displacement capacities. The effect of overturning on the column axial load and associated member capacities must be considered in the simplified model. Simplifying the demand and capacity models is not permitted if the structure does not meet the stiffness and period requirements in Sections 7.1.1 and 7.1.2.

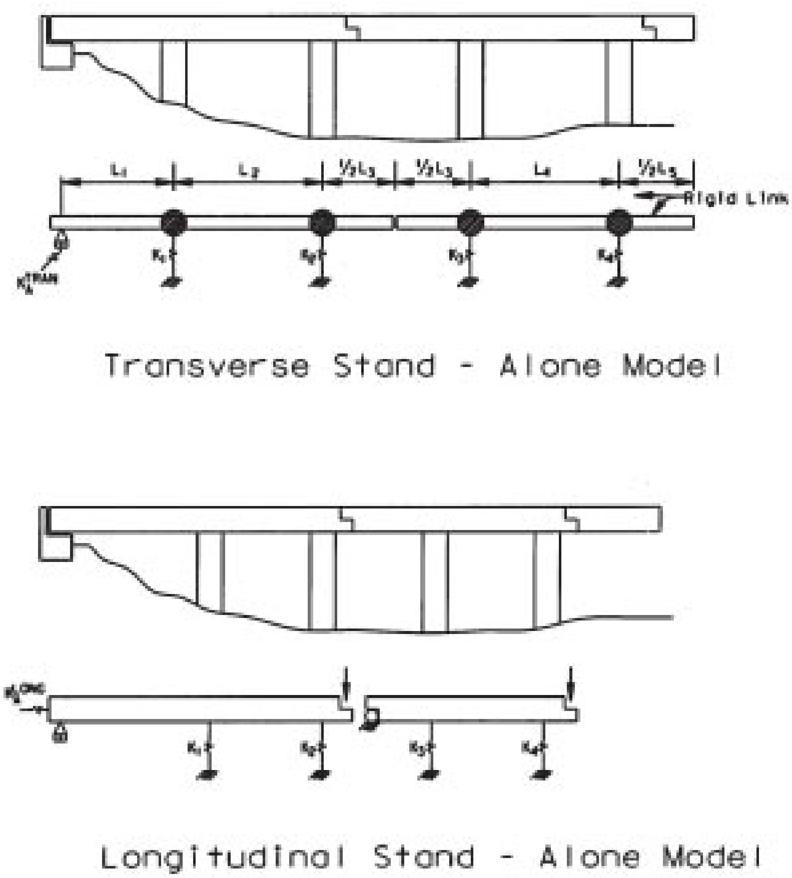

Figure 5.2 Stand-Alone Analysis

5.6 Effective Section Properties

5.6.1 Effective Section Properties for Seismic Analysis

Elastic analysis assumes a linear relationship between stiffness and strength. Concrete members display nonlinear response before reaching their idealized Yield Limit State.

Section properties, flexural rigidity $E_c I$ and torsional rigidity $G_c J$, shall reflect the cracking that occurs before the yield limit state is reached. The effective moments of inertia, I_{eff} and J_{eff} shall be used to obtain realistic values for the structure's period and the seismic demands generated from ESA and EDA analyses.

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5.6.1.1 I_{eff} for Ductile Members

The cracked flexural stiffness I_{eff} should be used when modeling ductile elements. I_{eff} can be estimated by Figure 5.3 or the initial slope of the M-ϕ curve between the origin and the point designating the first reinforcing bar yield as defined by equation 5.1

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$$E_c \times I_{eff} = \frac{M_y}{\phi_y} \qquad (5.1)$$

M_y = Moment capacity of the section at first yield of the reinforcing steel.

5.6.1.2 I_{eff} for Box Girder Superstructures

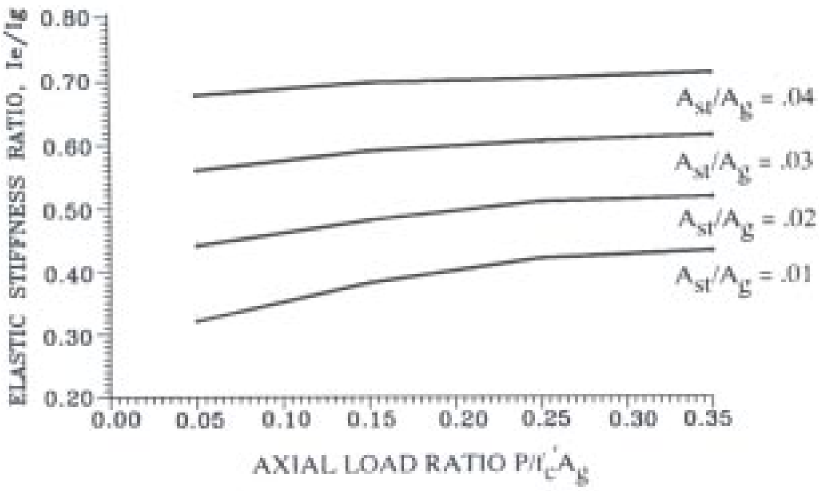
I_{eff} in box girder superstructures is dependent on the extent of cracking and the effect of the cracking on the element's stiffness.

I_{eff} for reinforced concrete box girder sections can be estimated between $0.5I_g - 0.75I_g$. The lower bound represents lightly reinforced sections and the upper bound represents heavily reinforced sections.

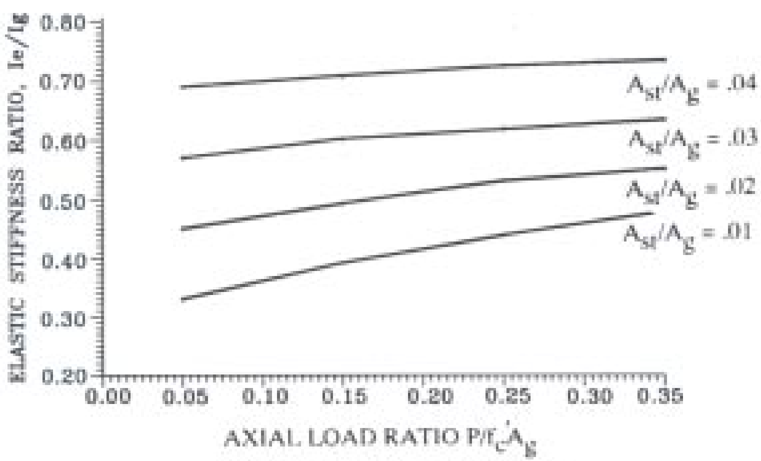
The location of the prestressing steel's centroid and the direction of bending have a significant impact on how cracking affects the stiffness of prestressed members. Multi-modal elastic analysis is incapable of capturing the variations in stiffness caused by moment reversal. Therefore, no stiffness reduction is recommended for prestressed concrete box girder sections.

5.6.1.3 I_{eff} for Other Superstructure Types

Reductions to I_g similar to those specified for box girders can be used for other superstructure types and cap beams. A more refined estimate of I_{eff} based on M-ϕ analysis may be warranted for lightly reinforced girders and precast elements.



a) Circular Sections



b) Rectangular Sections

Figure 5.3 Effective Stiffness of Cracked Reinforced Concrete Sections [7]

5.6.2 Effective Torsional Moment of Inertia

A reduction of the torsional moment of inertia is not required for bridge superstructures that meet the Ordinary Bridge requirements in Section 1.1 and do not have a high degree of in-plane curvature [7].

The torsional stiffness of concrete members can be greatly reduced after the onset of cracking. The torsional moment of inertia for columns shall be reduced according to equation 5.2.

$$J_{eff} = 0.2 \times J_g \tag{5.2}$$

5.7 Effective Member Properties for Non-Seismic Loading

Temperature and shortening loads calculated with gross section properties may control the column size and strength capacity often penalizing seismic performance. If this is the case, the temperature or shortening forces should be recalculated based on the effective moment of inertia for the columns.